Tracing Cosmic Evolution with Galaxy Clusters
ASP Conference Series, Vol. TBD, 2002
S. Borgani, M. Mezzetti & R. Valdarnini eds.

The REFLEX Cluster Survey: Probing the Mass Distribution in the Universe

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Abstract. We summarize some of the major results obtained so far from the REFLEX survey of X-ray clusters of galaxies, concentrating on the latest measurements of the cluster X-ray luminosity function and two-point correlation function. The REFLEX luminosity function provides the most homogeneous census of the distribution function of masses in the local Universe, representing a unique zero-redshift reference quantity for evolutionary studies. On the other hand, the observed clustering of REFLEX clusters is very well described by the correlation function of a low-Ω_M CDM model. Also, the bidimensional correlation map $\xi(r_p, \pi)$ shows no stretching along the line of sight, indicating negligible spurious effects in the sample, with at the same time a clear compression of the contours as expected in the presence of coherent motions.

1. The REFLEX Survey

The REFLEX[1] (ROSAT-ESO Flux-Limited X-ray) cluster survey is currently the largest sample of X-ray selected clusters of galaxies from the ROSAT All-Sky Survey with 1) a statistically homogeneous and fairly well-understood selection

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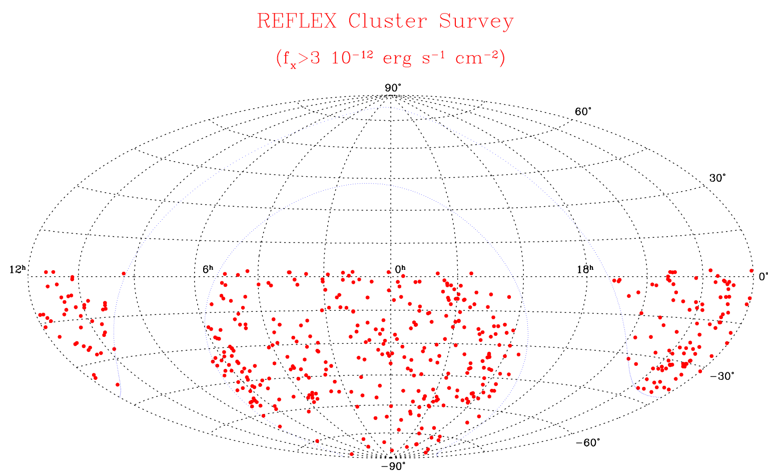

Figure 1. The sky distribution of REFLEX clusters. The dotted band marks the region of the galactic plane ($|b_{II}| > 20°$) which is excluded from the survey.

function; 2) measured redshifts. The survey contains 452 clusters over the southern celestial hemisphere ($\delta < 2.5°$), at galactic latitudes $|b_{II}| > 20°$ and is more than 90% complete to a flux limit of 3×10^{-12} erg s^{-1} cm^{-2} (in the ROSAT band, 0.1–2.4 keV). X-ray fluxes and source extensions were re-measured from the RASS with a dedicated algorithm, thus avoiding the limitations of the standard analysis software in the characterisation of extended sources. The details of the whole identification process and a critical discussion of potential sources of incompleteness are presented in Böhringer et al. (2001a). Redshifts for all but 3 REFLEX clusters have been measured during a long Key Programme (1992-2000) using ESO telescopes (e.g. Guzzo et al. 1999), that collected more than 3500 galaxy redshifts over almost 500 X-ray targets. Fig. 1 shows the distribution on the sky of the 452 clusters in the REFLEX survey, centered on the South Galactic Cap region (the largest contiguous area covered), while Fig. 2 plots their X-ray luminosity against their redshift. Given the survey flux limit (defined by the lower boundary of the point distribution), at large redshifts we are allowed to detect only the very bright, massive clusters. On the other hand, the very large solid angle of the survey allows for an extremely large volume to be explored (4.24 steradians, corresponding to 8.7×10^8 h^{-3} Mpc^3 out to $z = 0.3$ in an $\Omega_M = 0.3$, $\Omega_\Lambda = 0.7$ cosmology), such that these extremely rare objects on the tail of the cluster X-ray luminosity function have a significant probability to be detected. It is not by chance, in fact, that the most luminous cluster known is still that discovered by the REFLEX survey in 1994, i.e. RXCJ1347.4-1144 (Schindler et al. 1995). Another example is shown in Fig. 4. Such a large volume is also ideal for sampling the very large modes of density fluctuations in the Universe (Schuecker et al. 2001). From the distribution of Fig. 2 one can compute the mean density of clusters as a function of distance, which indicates a very good completeness (i.e. constant density) out to at least $z = 0.2$, possibly above. It is also evident how one can use the REFLEX survey to select sub-

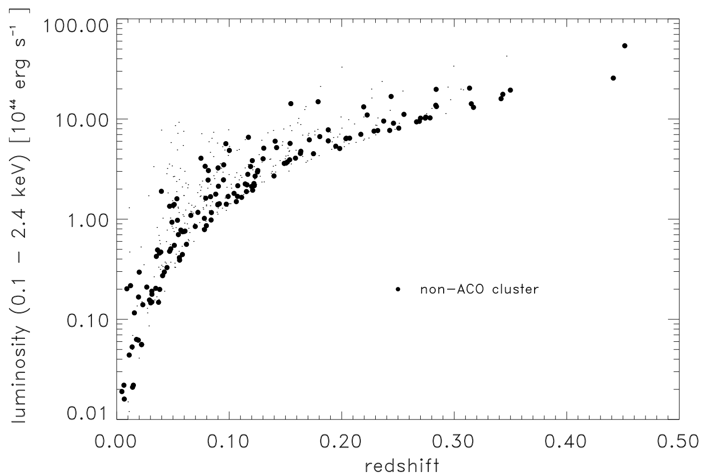

Figure 2. The distribution of X-ray luminosities (ROSAT band) as a function of redshift for all REFLEX clusters, with non-Abell clusters marked by filled circles. The two highest-redshift clusters are RXCJ1206.2-0848 at $z = 0.441$ (whose RGB image is shown in Fig. 4) and RXCJ1347.4-1144, the most X-ray luminous cluster currently known, at $z = 0.452$ (Schindler et al. 1995).

samples of clusters within well-defined ranges in L_X (i.e. mass) and redshift. A number of follow-up studies of this kind are indeed ongoing (see Böhringer et al. 2001b for an overview), and more will certainly follow when the catalogue is released in early 2002. The filled circles in Fig. 2 represent 142 clusters which do not appear in the visually-selected Abell/ACO catalogue (Abell 1958; Abell et al. 1989). It is interesting to see that these clusters are distributed basically at any redshift. This is a demonstration of how the "richness" criterion (the reason why most of these objects did not enter the Abell selection) is a poor indicator of the cluster mass, and how incomplete in mass a purely visually-selected cluster survey could be. We have also performed a direct X-ray analysis of the RASS data at all Abell-ACO cluster positions, measuring their X-ray flux. This gave the rather encouraging result that the REFLEX survey in fact detects *all* Abell-ACO clusters within its flux and area boundaries[2].

2. The Cluster X-ray Luminosity Function

The X-ray luminosity function (XLF) of galaxy clusters is an excellent observable incarnation of the cluster mass function, given that in clusters of galaxies X-ray luminosity is well related to the cluster mass (e.g. Reiprich & Böhringer 2002). For this reason, estimating the XLF was one of the prime targets of the REFLEX

[2]Even more, the REFLEX survey misses only 1 of the so-called Supplementary Abell clusters i.e. the extension to the main ACO catalogue, where those objects that did not meet all original criteria while still looking as *bonafide* clusters were listed.

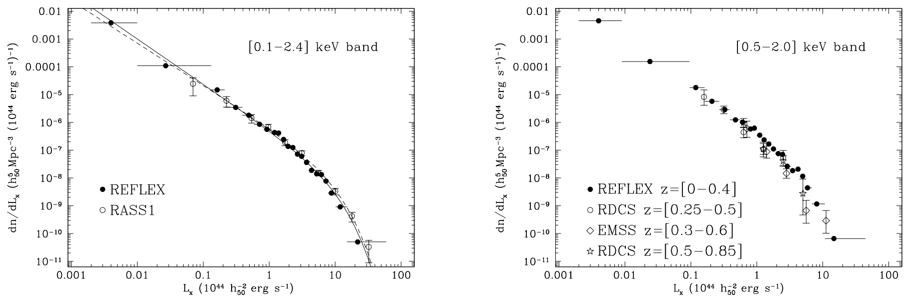

Figure 3. Left: The REFLEX cluster X-ray luminosity function (XLF, Böhringer et al. 2002), compared to the previous estimate obtained from the RASS1 Bright Sample, the brighter forerunner of REFLEX (De Grandi et al. 1999). Right: Comparison of the REFLEX XLF, with that of two representative distant cluster samples, the RDCS (Rosati et al. 1998) and EMSS (Henry et al. 1992), showing the moderate reduction in the number density of very luminous clusters at high redshifts. The REFLEX XLF is here computed in the [0.5–2.0] band, to allow for an homogeneous comparison.

survey. It was also one of the first results obtained by the project along the way, from the higher–flux RASS1 Bright Sample (De Grandi et al. 1999). The recent XLF from the whole survey (Böhringer et al. 2002) is compared to that early result in the left panel of Fig. 3. The improvement in the error bars of the latest REFLEX XLF (smaller than the size of the dots) gives an immediate idea of its quality. Such an accurate local measurement represents a standard reference of crucial importance for evolutionary studies, i.e. for comparison with XLF measured at high redshift. One such example is shown in the right panel of the same figure, where the REFLEX XLF is plotted together with those from the RDCS (Rosati et al. 1998) and EMSS (Henry et al. 1992) deep surveys. With the REFLEX data pivoting the local abundance, the evidence for mild evolution of the XLF bright end at high z can be tested to a high accuracy (e.g. Borgani et al. 2001; Henry 2001).

3. The Clustering of REFLEX Clusters

Clusters have a long history as tracers of large-scale structure (see Nichol, this volume) and, in particular, surveys of X-ray clusters have their own specific advantages (see Lahav et al. 1989 and Romer et al. 1994 for early applications, and Borgani & Guzzo 2001, Guzzo 2001 and Henry 2001 for recent reviews). First of all, once the characteristics of the X-ray instrument used are specified, a clean selection function can be constructed. This is by all means not an obvious task for an optically-selected survey. Second, fairly precise predictions can be made from the models for both the mass function and the clustering of objects above a given mass (see e.g. Borgani, this volume and Moscardini et al. 2000). These can be reliably translated into "observer space" in terms of X-ray

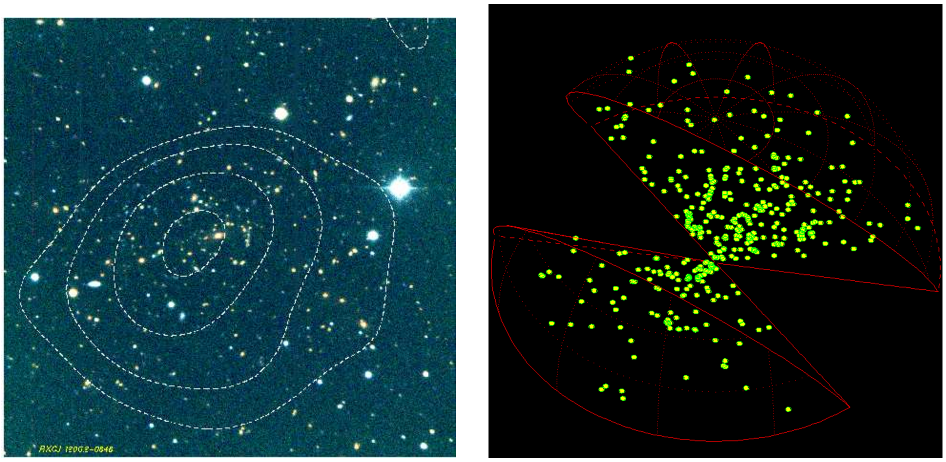

Figure 4. Left: BVR combined mage of the spectacular cluster RXCJ1206.2-0848, the second most distant object in the REFLEX survey, at z=0.441. Right: The spatial distribution of REFLEX clusters, out to 600 h^{-1} Mpc (plot from Borgani & Guzzo 2001). Note the presence of agglomerates and "chains", demonstrating the strong clustering of clusters among themselves.

luminosities and fluxes. These advantages allow one to select samples uniformly by mass over large areas (avoiding also other effects that plague optically-selected samples as line-of-sight projections), and provide the baseline for the REFLEX survey clustering results.

The right panel of Fig. 4 plots the 3D distribution of REFLEX clusters within a radius of 600 h^{-1} Mpc. Despite the fading with distance due to the flux-limited selection function, a number of superstructures with sizes 100 h^{-1} Mpc are evident: clusters are clearly still strongly clustered on such scales. This can be quantified by the two-point correlation function, that we plot for the whole flux-limited survey in Fig. 5 (Collins et al. 2000). The shape of ξ_{cc} is tightly constrained by the REFLEX data, and closely reproduces an amplified version of the galaxy two-point correlation function over almost two decades of scales, a classic prediction of biasing theory (Kaiser 1984). In the same figure, we also plot the predictions of two low-density CDM models from Moscardini et al. (2000), which are able to correctly reproduce both the shape and amplitude of the observed REFLEX ξ_{cc}. We remark that in this case the amplitude is not a free parameter as for galaxy correlation functions, since the bias value for the specific REFLEX selection function can be computed using an appropriate theory for the clustering of massive haloes (e.g. Mo & White 1996 and subsequent refinements), given the fairly straightforward relation between X-ray luminosity and mass (see Borgani & Guzzo 2001 for more details and references). Analogous results have been obtained from the power spectrum, as discussed in the contribution by P. Schuecker to this volume (and in detail by Schuecker et al. 2001). Another prediction which can be precisely made for a survey like REFLEX is the dependence of the correlation length on the survey flux limit. The expectation values for different CDM variants are compared to

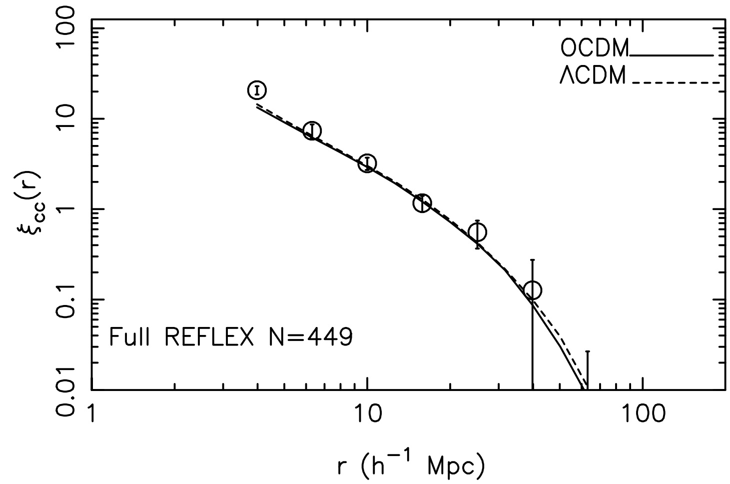

Figure 5. The REFLEX two-point correlation function compared with the predictions for the same survey selection function of two low-density CDM models, respectively open with $\Omega_m = 0.3$, $\Omega_\Lambda = 0.0$ (OCDM) and flat with $\Omega_m = 0.3$, $\Omega_\Lambda = 0.7$ (ΛCDM), as computed by Moscardini et al. (2000). (Here r is the redshift-space separation, usually called s in galaxy surveys.)

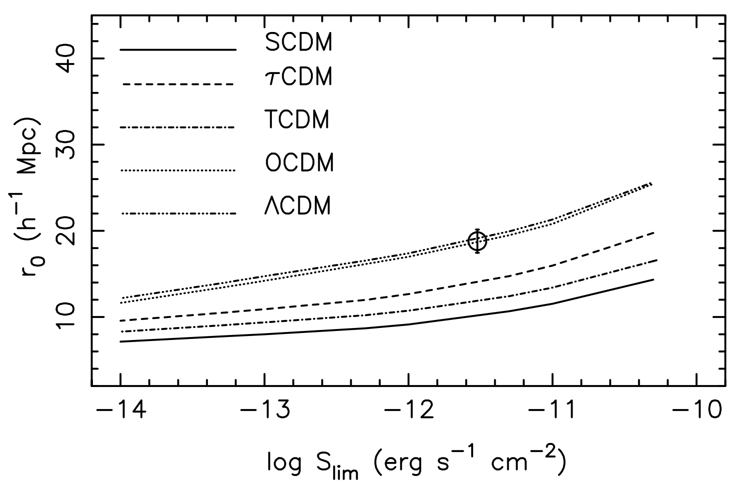

Figure 6. Comparison of the value of correlation length r_0 from the full REFLEX flux-limited survey with the predictions as a function of limiting X-ray flux for a range of CDM-type cosmological models computed by Moscardini et al. (2000).

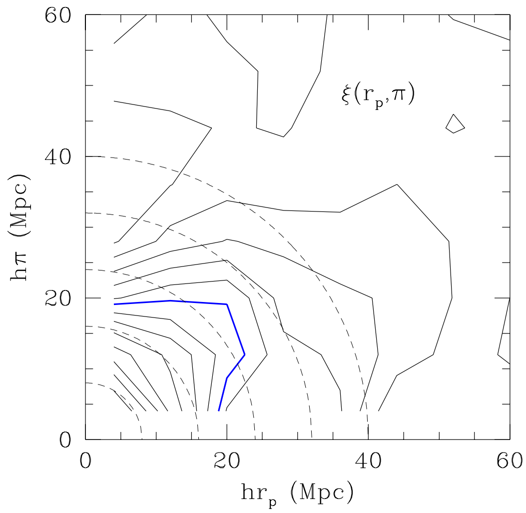

Figure 7. The bi-dimensional correlation function $\xi(r_p, \pi)$, used to evidence redshift-space anisotropies in the clustering of REFLEX clusters. The diagram shows no stretching of the contours along the line of sight, indicating that projection biases and redshift errors are small in the REFLEX survey. On the contrary, the evident large-scale compression is a possible fingerprint of coherent motions. The dashed circles show how a perfectly isotropic distribution would look like.

the observed correlation length from the full REFLEX in Fig. 6, again indicating that low-Ω_M models provide the best consistency with observations (Collins et al. 2000).

Redshift-space anisotropies in the clustering pattern of clusters can be evidenced through the bidimensional correlation function $\xi(r_p, \pi)$ [or analogously $\xi(\sigma, \pi)$]. Classical analyses of Abell samples show strong elongations along the line-of-sight π direction (e.g. Miller et al. 2001), which are typically not seen in automatic cluster catalogues (e.g. Nichol et al. 1992). These arise by a combination of projection effects, redshift errors and true spatial anisotropies in small–size catalogues. The plot of $\xi(r_p, \pi)$ for REFLEX (Fig. 7), in fact shows no evidence for stretching along the line of sight, indicating how these spurious effects are negligible in this survey. On the other hand, the contours are significantly compressed at large separations, a typical signature of streaming motions (proportional to the quantity $\beta = \Omega_M^{0.6}/b$) which is for the first time seen in a cluster sample (Guzzo et al. 2002; see also Padilla & Baugh 2001).

We would like to conclude by mentioning that the statistical quality of the results presented here will significantly improve in the near future, thanks to the extension of REFLEX to fainter fluxes (by a factor ~ 2). The REFLEX-2 sample is in fact being constructed and will bring the total number of clusters over the same area to ~ 800 (see e.g. Böhringer et al. 2001b).

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